

Tunable and Low-Noise WSe₂ Quantum Emitters for Quantum Photonics

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Low-noise and tunable single-photon sources are essential components of photonic quantum technologies. However, in WSe₂ quantum emitters, charge noise from fluctuations in their local electrostatic environment remains a major obstacle to achieving transform-limited single-photon emission and high photon indistinguishability. Here, we systematically investigate two noise mitigation strategies in hexagonal boron nitride (*h*-BN): encapsulation and electrostatic biasing. We demonstrate that *h*-BN encapsulation alone suppresses spectral wandering (from ~ 170 μ eV to ~ 40 μ eV) and narrows emission linewidths (from ~ 524 μ eV to ~ 120 μ eV), while applied bias enables stable Stark tuning over a 280 μ eV range and further linewidth narrowing down to ~ 100 μ eV, reaching the resolution-limited regime. Time-resolved and second-order correlation measurements confirm stable monoexponential decay and high single-photon purity [$g^{(2)}(0) \sim 0.01$] with no observable blinking. To quantify progress toward the transform limit, we define two figures of merit—the linewidth ratio $R = W_{\text{exp}}/W_{\text{dec}}$ and total broadening $\Delta W = W_{\text{exp}} - W_{\text{dec}}$ —with both being reduced more than fivefold in optimized devices. These results provide a robust framework for developing and evaluating low-noise, tunable WSe₂ quantum emitters, potentially realizing electrically controllable sources of indistinguishable single photons for future photonic quantum technologies.

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I. INTRODUCTION

High-performance single-photon sources are fundamental building blocks for photonic quantum technologies [1–4], enabling a wide range of applications in quantum communications and quantum information processing. For most applications—particularly those involving quantum interference such as photonic logic or entanglement swapping—photon indistinguishability is a critical requirement. III-V semiconductor quantum dots have demonstrated near-unity purity and indistinguishability when integrated with optical cavities and operated under advanced excitation schemes [5–10]. However, their reliance on advanced epitaxial growth techniques and complex nanofabrication poses challenges for large-scale deployment and integration.

In recent years, two-dimensional semiconductors, particularly transition metal dichalcogenides (TMDs), have

emerged as a highly promising platform for developing on-demand single-photon sources [11–13]. These materials offer several advantages, including large exciton binding energies, valley degrees of freedom, robust trion formation, and the ability to form heterostructures and moiré excitons [11,14–16]. Additionally, their van der Waals stacking nature allows their direct integration into a wide range of photonic nanostructures and cavities [17].

Single-photon emission in TMDs typically originates from localized excitonic states, often formed through the interplay between defects and local strain. Theoretical models suggest that hybridization between defect states and strain-localized dark excitons can result in brightening of these dark states, thereby enabling single-photon emission [18,19]. Building on this physical origin, a wide range of engineering techniques has been developed to realize such states in a controlled manner. These include imaginative strain-engineering approaches, including AFM indentation [20,21], nanostructures [22–25], nanoparticles [26–28], piezoelectric substrates [29], and plasmonic nanostructures [30,31] as well as deterministic defect creation via high-energy irradiation (e.g., electron irradiation [22,23,27], helium ion irradiation [32,33], or UV exposure [34]).

These approaches have enabled the site-specific generation of linearly polarized sources with high single-photon

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purity across different TMD materials [22,32,33,35,36]. Moreover, the emission energies of these quantum emitters are readily tunable via mechanical strain, electrical gating, or magnetic fields [37–40].

Despite promising advances, reported indistinguishability values for TMD quantum emitters remain low, around 2% [41]. A key limiting factor is emission linewidth broadening, driven by mechanisms such as phonon-induced dephasing and spectral diffusion from local charge fluctuations [5], with charge noise identified as the dominant contributor [42]. “Broadening” refers to the deviation of the experimental linewidth W_{exp} from the ideal transform-limited value W_{rad} , which is fundamentally set by the radiative lifetime. In TMDs, lifetimes range from less than 1 ns to tens of nanoseconds [22,32,36,43–46], due to differences in their microscopic origins and complex recombination dynamics, corresponding to W_{rad} values of 0.01–10 μeV . In contrast, measured linewidths typically lie between several hundred and a few thousand microelectronvolts [23,43,45,47], revealing a mismatch of several orders of magnitude.

Recent studies suggest that strategies such as *h*-BN encapsulation and electrostatic biasing can suppress these fluctuations and reduce W_{exp} by stabilizing the local electrostatic environment [32,37–39,48]. However,

a comprehensive and quantitative evaluation of how different noise mitigation approaches bring TMD quantum emitters closer to the transform limit remains an open challenge.

In this work, we systematically investigate how *h*-BN encapsulation and electrostatic biasing can mitigate charge noise in WSe₂ quantum emitters. By combining passive dielectric screening with active tuning of the local electrostatic environment, we achieve significant improvements in emitter performance. We show that *h*-BN encapsulation alone minimizes spectral diffusion, from $\sim 170 \mu\text{eV}$ down to $\sim 40 \mu\text{eV}$, while also narrowing the emission linewidth from $\sim 500 \mu\text{eV}$ to $\sim 150 \mu\text{eV}$. Time-resolved measurements reveal a monoexponential decay, pointing to a stabler surrounding charge environment and less complex decay dynamics. Moreover, second-order correlation measurements confirm high single-photon purity [$g^{(2)}(0) \sim 0.01$] with no observable bunching, indicating the absence of blinking. Electrostatic biasing further enhances performance in encapsulated devices, enabling resolution-limited linewidths in the range of $\sim 100 \mu\text{eV}$ and stable Stark tuning over a range of 280 μeV . To quantify these improvements, we introduce two figures of merit: the linewidth ratio $R = W_{\text{exp}}/W_{\text{dec}}$ and the excess broadening $\Delta W = W_{\text{exp}} - W_{\text{dec}}$. Combined encapsulation and

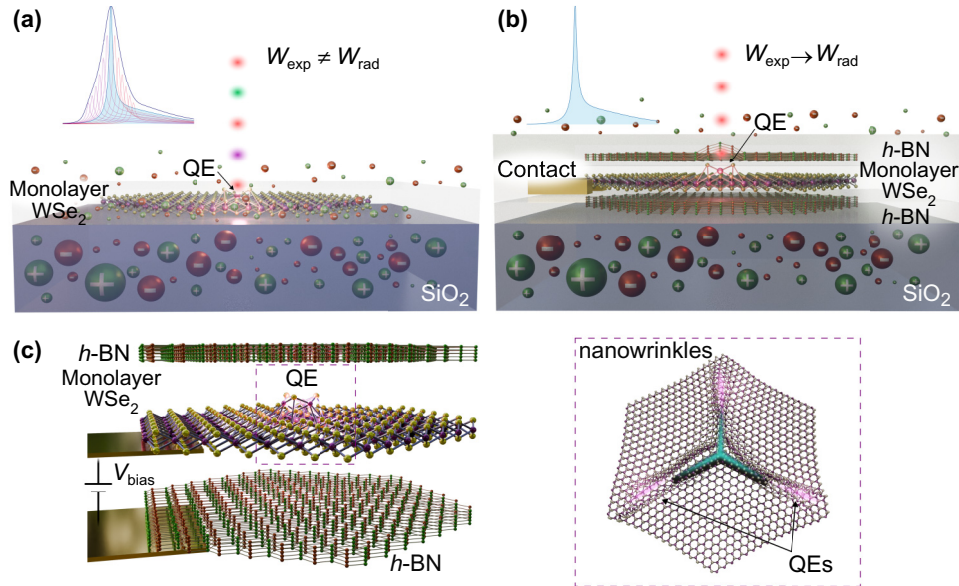


FIG. 1. System under study. (a) WSe₂ monolayer on a SiO₂ substrate in an unstable charge environment. The presence of fluctuating charges perturbs the quantum emitter (QE), leading to inhomogeneous broadening through spectral diffusion, which leads to a deviation from lifetime-limited emission. This effect is illustrated by the variation in photon colors. The corresponding photoluminescence spectrum exhibits a broadened peak, where the measured linewidth (dark blue) exceeds the radiative lifetime-limited linewidth (light blue). (b) WSe₂ monolayer encapsulated in few-layer hexagonal boron nitride (*h*-BN) on a SiO₂ substrate. The *h*-BN encapsulation isolates the monolayer from the surrounding fluctuating charges, while a gold contact enables the application of an external bias to further stabilize the charge environment. As a result, the emitter experiences minimal spectral diffusion (uniform photon colors). The corresponding photoluminescence spectrum is significantly narrower, with W_{exp} approaching W_{rad} (lifetime-limited emission linewidth), indicating a reduction in spectral broadening effects. (c) Fully encapsulated device, with the inset illustrating the strain-engineered WSe₂ monolayer hosting the quantum emitters.

biasing reduce both metrics more than fivefold, with R decreasing from 4314 to 860 and ΔW decreasing from 474.5 to 92.8 μeV . While ΔW reaches values comparable to the state of the art due to a narrow experimental linewidth W_{exp} , R remains modest, limited by the relatively long radiative lifetime (~ 6 ns) under above-band excitation. Nevertheless, we discuss clear routes for reaching transform-limited performance via advanced excitation schemes and Purcell-enhanced emission. These findings establish a robust framework for developing low-noise, tunable WSe₂ quantum emitters, potentially enabling electrically controlled sources of indistinguishable single photons for future photonic quantum information technologies.

II. RESULTS

A. System under study

Figure 1(a) depicts a bare WSe₂ monolayer hosting a quantum emitter, on a standard SiO₂/Si substrate. In this configuration, the emitter is highly susceptible to charge noise arising from trapped charges in the substrate and free carriers within the host monolayer WSe₂ itself. These fluctuating charges generate local electric fields

that shift the exciton energy via the quantum-confined Stark effect, leading to temporal spectral fluctuations and linewidth broadening [22,23,45,49]. As a result, the emission deviates significantly from the transform-limited regime, simultaneously reducing coherence and indistinguishability [5,49]. To mitigate this charge noise, we implement two complementary strategies, as illustrated in Fig. 1(b): (1) passive electrostatic screening through *h*-BN encapsulation and (2) active electrostatic control via applied electrical bias.

To evaluate the impact of each approach, we fabricated two devices, device A and device B, each with its own monolayer WSe₂ quantum emitters formed via deterministic strain engineering on nanopillar arrays [Fig. 1(c), purple inset] on typical SiO₂/Si substrates, as detailed in our previous work [22]. Device A consists of a bare WSe₂ monolayer directly interfaced with pre-patterned gold electrodes, such that the monolayer is in direct contact with one electrode and in close proximity to the second, enabling active biasing without dielectric isolation. Device B shares the same electrode configuration, but the WSe₂ monolayer is encapsulated between relatively thin (three to five layers) *h*-BN flakes. This encapsulation adds dielectric screening, while maintaining electrical access to the monolayer, thus

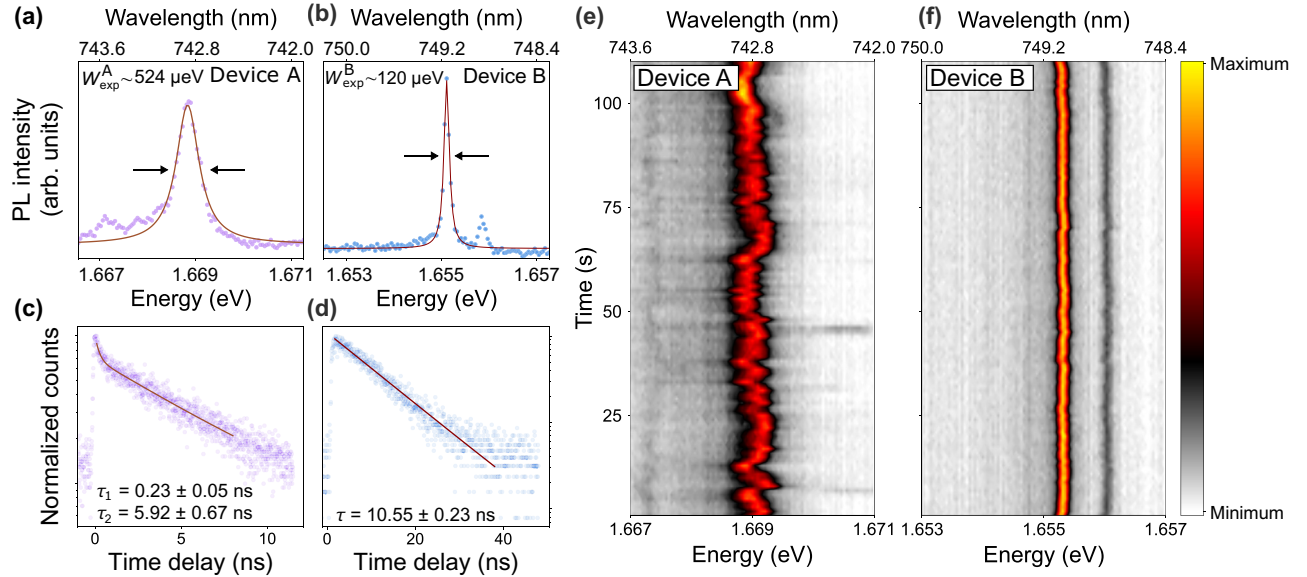


FIG. 2. Comparison between unencapsulated (device A) and encapsulated (device B) WSe₂ quantum emitters. (a),(b) High-resolution photoluminescence (PL) spectra at 4 K for exemplary unencapsulated [(a)] and encapsulated [(b)] quantum emitters, referred to as devices A and B, respectively. Both spectra are fitted with a Lorentzian curve, revealing a linewidth of 0.233 ± 0.008 nm for device A and 0.054 ± 0.002 nm for device B. (c),(d) Time-resolved photoluminescence measurements for devices A and B. Device A [(c)] exhibits a biexponential decay, with an initial fast decay of $\tau_1 = 0.23 \pm 0.06$ ns, dominated by a long decay component of $\tau_2 = 5.92 \pm 0.67$ ns. Device B [(d)] shows simpler single-exponential decay dynamics with a calculated decay time of $\tau = 10.55 \pm 0.23$ ns. (e),(f) High-resolution photoluminescence time trace signal for devices A and B, collected over 110 s with an integration time of 1 s per frame. Device A [(e)] shows relatively unstable emission, with a spectral wandering of $290 \mu\text{eV}$ around a central wavelength of 742.831 ± 0.039 nm. Device B [(f)] exhibits greater stability, with a spectral wandering of $70 \mu\text{eV}$ and a central wavelength of 749.072 ± 0.006 nm. All spectra are collected with the use of a 650 nm pulsed laser excitation scheme. For the lifetime measurements, a repetition rate of 80 MHz is used for device A and a repetition rate of 20 MHz is used for device B.

combining passive environmental stabilization with active charge control. It is worth noting that *h*-BN encapsulation over strain-engineered monolayers presents specific fabrication challenges, as its high bending rigidity [50] impedes conformal wrapping over nanopillars for nanowrinkle formation [49]. We addressed this by adapting the nanopillar geometry (increased height, longer tips) to accommodate a thin (two to three layers) bottom *h*-BN flake, followed by transfer of the WSe₂ monolayer and a thicker (five to eight layers) top *h*-BN cap. Full fabrication procedures are detailed in Sec. V.

B. Passive noise mitigation via *h*-BN encapsulation

First, to evaluate the impact of *h*-BN encapsulation in mitigating charge noise, we compare representative quantum emitters from device A (unencapsulated) and device B (fully encapsulated) under zero applied bias. Figures 2(a) and 2(b) present micro-photoluminescence (μ PL) spectra recorded at $T = 4$ K under 650 nm continuous wave (CW) excitation with an integration time of ~ 0.8 s. The emitter in device A exhibits a relatively broad emission linewidth, likely caused by spectral diffusion due to an unstable charge environment. In contrast, the emitter in device B shows a significantly narrower linewidth, indicating reduced charge noise due to electrostatic screening provided by the *h*-BN encapsulation. To quantify this difference, we fit the μ PL spectra with Lorentzian functions and extract the experimental full width at half maximum, denoted as W_{exp} . Device A yields $W_{\text{exp}} = 524 \pm 18 \mu\text{eV}$ (0.233 ± 0.008 nm) centered at 742.868 ± 0.003 nm, whereas device B shows a substantially smaller $W_{\text{exp}} = 125 \pm 4 \mu\text{eV}$ (0.054 ± 0.002 nm) at 749.159 ± 0.001 nm. This fourfold reduction in linewidth could suggest significant suppression of charge-induced broadening due to the dielectric screening provided by *h*-BN encapsulation. To examine secondary effects of encapsulation on the charge environment, Fig. 1 in Supplemental Material [51] compares the long-range spectra of devices A and B. We observe that encapsulation reduces the density of active sites, yet, as indicated in Figs. 2(a) and 2(b), the remaining emitters consistently exhibit narrower linewidths. Moreover, to assess the effects of temperature on the encapsulated system, Fig. 2 in Supplemental Material [51] presents μ PL spectra of the exemplary emitter recorded at different temperatures. In addition, a phonon side peak consistently accompanies the main emission line in all encapsulated emitters, as will become evident throughout this work and is further discussed in Note 7 in Supplemental Material [51].

To further investigate the underlying recombination dynamics of the emitters in both devices, we performed time-resolved photoluminescence (TRPL) measurements under 650 nm above-band pulsed excitation. Figure 2(c)

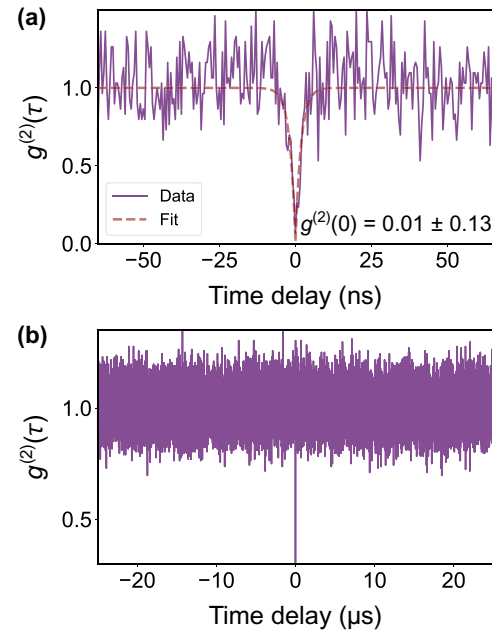


FIG. 3. Second-order autocorrelation [$g^{(2)}(\tau)$] measurement under CW excitation for the exemplary emitter in device B. (a) Short time delay range (± 60 ns) autocorrelation measurement. The measurement is normalized by dividing the coincidence counts by the calculated average over the extended time period. The fit (dashed red line) reveals $g^{(2)}(0) = 0.01 \pm 0.13$, indicating a high single-photon purity of 99% with the absence of any noticeable photon bunching. (b) The same autocorrelation measurement as in (a) on a longer timescale ($\pm 25 \mu\text{s}$), showing no blinking or variations, demonstrating the emitter's exceptional photostability over extended periods.

shows the TRPL trace for device A, which displays complex decay behavior characterized by both fast and slow components. A biexponential fit yields a dominant slow component of $\tau_2 = 5.92 \pm 0.67$ ns, in line with typical reported values for WSe₂-based quantum emitters [44,47,52,53]. The minor fast component of $\tau_1 = 0.23 \pm 0.06$ ns could be associated with nonradiative recombination pathways mediated by trap states and fluctuating charges in the vicinity of the emitter due to direct contact with a substrate [22,45]. On the other hand, device B [Fig. 2(d)] exhibits a simpler monoexponential decay with a lifetime τ of 10.55 ± 0.23 ns, suggesting a suppression of nonradiative processes and an enhanced stability of the local charge environment, likely due to the *h*-BN encapsulation.

To assess the effects of *h*-BN encapsulation on the emitters' spectral stability over longer timescales, we recorded PL time traces under 650 nm CW excitation with an integration time of ~ 0.8 s per frame. Figures 2(e) and 2(f) show results for devices A and B, respectively. Device A exhibits pronounced spectral wandering, while device B maintains a much stabler and narrower emission, consistent with earlier observations [49]. To quantify this

behavior, we fit each time frame with a Lorentzian function to extract the central wavelength and linewidth of the emission over time. As shown in Fig. 3 in Supplemental Material [51], the fitted results reveal a pronounced contrast between the two devices. Device A exhibits a broader spectral wandering of $172 \mu\text{eV}$ for the emission line centered at $742.831 \pm 0.039 \text{ nm}$, which is calculated as 2σ , where σ is the standard deviation of the Gaussian. On the other hand, device B shows a threefold improvement with substantially reduced wandering down to $50 \mu\text{eV}$ centered at $749.071 \pm 0.006 \text{ nm}$. Moreover, the average linewidths also differ clearly, with device A exhibiting $452 \pm 58 \mu\text{eV}$ ($0.201 \pm 0.026 \text{ nm}$) and device B showing a significantly narrower linewidth of $132.5 \pm 13.3 \mu\text{eV}$ ($0.060 \pm 0.006 \text{ nm}$), in good agreement with the single-shot spectra presented in Figs. 2(a) and 2(b). These results demonstrate the importance of charge noise mitigation in these TMD single-photon emitters and provide important insights toward achieving transform-limited single-photon emission.

Next, to gain deeper insight into the single-photon emission properties of the encapsulated emitter in device B, we performed a second-order correlation measurement under 650 nm CW excitation. Figure 3(a) shows the measured $g^{(2)}(\tau)$ over a short time window, revealing pronounced antibunching at zero delay with $g^{(2)}(0) = 0.01 \pm 0.13$, confirming high single-photon purity of $\sim 99\%$. For comparison, Fig. 4 in Supplemental Material [51] shows a representative $g^{(2)}(\tau)$ measurement from an unencapsulated emitter, demonstrating relatively high purity of $\sim 90\%$. Beyond the antibunching, $g^{(2)}(\tau)$ measurements also provide additional information about the emitter's recombination dynamics [54]. For instance, the presence of photon bunching can indicate emission blinking, typically associated with substantial nonradiative recombination processes arising from an unstable charge environment, where fluctuating charges or trap states momentarily quench the emission [54,55]. In the case of device B, no bunching is observed, which may suggest stable emission dynamics without blinking on this short timescale. This observation is consistent with prior studies showing that the presence of bunching in WSe₂-based quantum emitters is typically associated with the absence of h -BN encapsulation, whereas its suppression is commonly observed in encapsulated devices [23, 28,49,56]. However, the second-order correlation measurements over shorter timescales do not fully capture potential blinking over longer durations. To assess this case, we extended the $g^{(2)}(\tau)$ measurement to a broader time window. As shown in Fig. 3(b), the second-order correlation measurement $g^{(2)}(\tau \neq 0)$ remains flat over tens of microseconds, with no observable bunching. This behavior points to stable single-photon emission dynamics in device B, with no evidence for blinking, even at longer timescales ($\pm 25 \mu\text{s}$), highlighting the effectiveness

of h -BN encapsulation as a passive noise mitigation strategy.

C. Active noise mitigation and tuning via electrical biasing

Next, we investigate the role of electrical biasing in mitigating charge noise and modulating the emitter's optical properties. Figure 4(a) presents μPL spectra ($T = 4 \text{ K}$, 650 nm CW laser excitation) from device A, measured at $V_{\text{bias}} = 0 \text{ V}$ and $V_{\text{bias}} = +20 \text{ V}$. Upon applying a positive bias, we observe a Stark-induced redshift of the emission spectrum accompanied by noticeable spectral broadening. Interestingly, the application of negative bias to device A does not result in any noticeable change in the emission, likely due to an asymmetric local charge environment preferentially responding to one bias direction. To further investigate the effect of positive bias, we performed Lorentzian fits to the emission spectra at 0 and $+20 \text{ V}$. The extracted results confirm our initial observations and show a clear spectral broadening, with W_{exp} increasing from $283 \pm 20 \mu\text{eV}$ ($0.126 \pm 0.009 \text{ nm}$) at 0 V to $370 \pm 39 \mu\text{eV}$ ($0.165 \pm 0.018 \text{ nm}$) at $+20 \text{ V}$. Additionally, the fits also reveal a Stark-induced redshift of $\sim 100 \mu\text{eV}$.

To assess the temporal stability of this Stark shift effect, we recorded a PL time trace, shown in Figure 4(c). Upon application of $V_{\text{bias}} = +20 \text{ V}$ at $t \sim 30 \text{ s}$, the emission exhibits an immediate redshift; however, significant spectral fluctuations persist, and the intensity drops sharply. This reduction may arise from decreased oscillator strength or reduced exciton capture efficiency, potentially due to carrier depletion or suppression of the local potential well under a positive bias [57]. Moreover, the emission line gradually drifts back toward its original position, despite the active biasing until $t \sim 85 \text{ s}$. This behavior suggests a dynamically unstable charge environment that mimics capacitor-like charging and discharging, rather than maintaining a stable electric field, highlighting the limited effectiveness of electrical biasing in unencapsulated devices on a Si/SiO₂ substrate.

On the other hand, device B exhibits a markedly different behavior under applied bias. Figure 4(b) presents normalized μPL spectra under $V_{\text{bias}} = 0 \text{ V}$, $+10 \text{ V}$, and -10 V . In contrast to device A, the encapsulated emitter responds symmetrically to both polarities, maintaining a narrow emission linewidth. Lorentzian fits yield $W_{\text{exp}} = 108 \pm 4 \mu\text{eV}$ ($0.049 \pm 0.002 \text{ nm}$) at $V_{\text{bias}} = -10 \text{ V}$ and $W_{\text{exp}} = 101 \pm 6 \mu\text{eV}$ ($0.045 \pm 0.003 \text{ nm}$) at $V_{\text{bias}} = +10 \text{ V}$. These values are at the lower limit of what our spectroscopic setup can resolve (Horiba iHR550, 1200 grooves/mm grating), as determined both from the manufacturer's specifications at 750 nm ($\sim 110 \mu\text{eV}$) and from our independent calibration using an ultranarrow laser (Fig. 5 in Supplemental Material [51]). We therefore

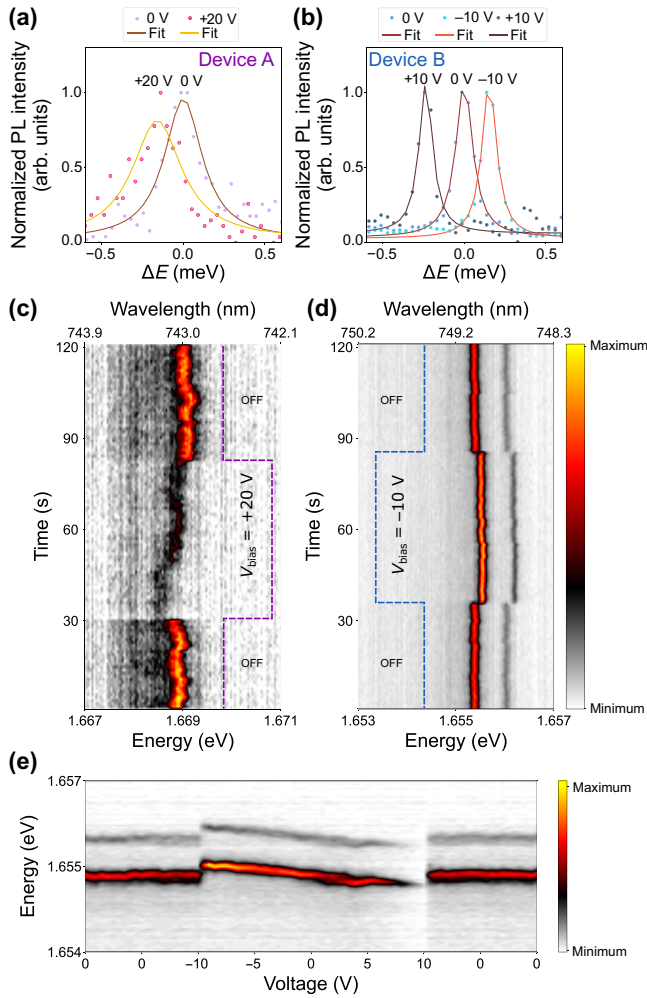


FIG. 4. Bias effects on photoluminescence (PL) for unencapsulated (device A) and encapsulated (device B) WSe₂ quantum emitters. (a),(b) High-resolution photoluminescence spectra with Lorentzian fitting under different biases. In device A (a), a +20 V bias shifts the zero-phonon line to lower energies, while presenting a slight linewidth increase. Device B (b) shows a symmetric response: -10 V and +10 V shift the zero-phonon line to higher and lower energies, respectively. (c),(d) Photoluminescence time traces under bias. Device A (c) exhibits an initial zero-phonon line shift to lower energies, reverting to its original position with reduced intensity. Device B (d) shows a stable ZPL shift to higher energies with increased intensity under -10 V bias. (e) Photoluminescence time trace for device B under varied bias (-10 to +10 V over 40 s). The zero-phonon line shifts linearly (linear Stark effect), with the intensity dropping above +7 V. Data collected at 4 K under 650 nm CW laser excitation.

argue that the measured linewidths are resolution limited. In comparison, at zero bias, the emitter displays a slightly broader linewidth of $125.07 \pm 4.14 \mu\text{eV}$ ($0.057 \pm 0.002 \text{ nm}$), in close agreement with the results in Fig. 2.

The emitter's stability under negative bias is further examined in the μPL time trace shown in Figure 4(d).

Upon application of $V_{\text{bias}} = -10 \text{ V}$ at $t \sim 30 \text{ s}$, the emission peak undergoes an immediate blueshift of approximately $146 \mu\text{eV}$ and remains remarkably stable for the entire 50 s bias interval, before returning to its original position once the bias is removed. Notably, the emission intensity increases under bias, suggesting enhanced radiative decay, potentially due to the suppression of non-radiative decay channels. We use the same fitting procedure as used for the time traces in Fig. 2, which reveals an average experimental linewidth $\mathcal{W}_{\text{exp}}$ of $104 \pm 5 \mu\text{eV}$ ($0.047 \pm 0.002 \text{ nm}$), in close agreement with the snapshot presented in Fig. 4(b). In addition, the fits yield a spectral wandering of $39 \mu\text{eV}$, centered at an average emission wavelength of $749.005 \pm 0.008 \text{ nm}$. The time trace in Fig. 4(d) already shows resolution-limited linewidths, indicating strong suppression of spectral diffusion. To rigorously benchmark this performance, we performed high-resolution μPL measurements using a 1200 grooves/mm grating and 0.25 s integration time, depicted in Fig. 6(a) in Supplemental Material [51]. The extracted parameters via Lorentzian fits reveal an average linewidth narrowing by $\sim 25\%$ under bias [Fig. 6(b) in Supplemental Material [51]], reaching the resolution limit at $99 \pm 8 \mu\text{eV}$, in agreement with the value extracted from Fig. 4(b). Analysis of the central wavelength drift [Fig. 6(c) in Supplemental Material [51]] further confirms the long-term spectral stability, with spectral diffusion remaining constant at $\sim 40 \mu\text{eV}$ under bias. These results confirm that continuous electrical bias does not compromise long-timescale spectral stability, while allowing the emitter to maintain resolution-limited emission.

To investigate the response of device B under dynamic bias modulation, we recorded a PL time trace [Fig. 4(e)] during a linear voltage sweep from $V_{\text{bias}} = -10 \text{ V}$ to $V_{\text{bias}} = +10 \text{ V}$ over 40 s (0.5 V step/frame), with an integration time of $\sim 0.8 \text{ s}$ per frame. The emission energy shifts linearly and symmetrically with bias polarity, consistent with the linear Stark effect. However, the intensity drops sharply beyond $V_{\text{bias}} = +7 \text{ V}$, and the emission is nearly quenched at $V_{\text{bias}} = +10 \text{ V}$, which, similarly to device A, could be attributed to a possible excess charge imbalance activating nonradiative recombination channels, a reduction of the oscillator strength, or induction of a transition between other excitonic states, such as from neutral to charged excitons (or vice versa). To further evaluate how external bias influences the overall density of quantum emitters in an encapsulated device, Fig. 7 in Supplemental Material [51] presents a long-range μPL intensity map acquired under a linear sweep from $V_{\text{bias}} = -10 \text{ V}$ to $V_{\text{bias}} = +10 \text{ V}$. No additional emitters appear with the application of bias, but the quenching of certain emitters is already visible. The quenching behavior is studied further in a broader sweep range ($V_{\text{bias}} = [-20, +20] \text{ V}$) depicted in Fig. 8 in Supplemental Material [51], with the rapid

recovery, once the bias is removed, confirming the emitter's resilience.

To further assess the reproducibility of the tuning response, we analyzed additional emitters under both voltage ranges ($V_{\text{bias}} = [-10, +10]$ V and $V_{\text{bias}} = [-20, +20]$ V), as shown in Fig. 9 in Supplemental Material [51], with exact quenching thresholds varying. Some emitters, such as Q3, exhibit distinct responses, likely due to differences in their initial excitonic states (neutral or positively or negatively charged states) or variations in the local electrostatic environment.

To quantitatively analyze the trends observed in the voltage sweep in Fig. 4(e), we conducted a detailed analysis using the same fitting procedure as for Fig. 4(d), the results of which are presented in Fig. 10 in Supplemental Material [51]. In Fig. 10(a) in Supplemental Material [51], we observe a symmetric narrowing of the experimental linewidth W_{exp} with increasing bias magnitude, consistently reaching the spectrometer's resolution limit near $V_{\text{bias}} = \pm 10$ V. This behavior aligns with observations from both static bias snapshots and constant-bias time traces. Figure 10(b) in Supplemental Material [51] shows the extracted emission energies as a function of bias, revealing a linear and symmetric Stark shift with maximum detuning around ± 140 μeV . In addition, Fig. 10(c) in Supplemental Material [51] presents TRPL measurements under various bias conditions, revealing lifetime bias-driven modulations of up to $\pm 40\%$, indicative of field-induced changes in recombination dynamics through the modification of the local charge environment. These extracted lifetimes are used to calculate the Fourier-limited linewidths W_{dec} in the following section, where we systematically evaluate the extent to which each noise mitigation strategy brings the emission from TMD quantum emitters toward the transform limit.

D. Toward lifetime-limited PL

Having demonstrated the effects of h -BN encapsulation and electrical biasing on the optical properties of WSe₂ quantum emitters, we now assess how closely their single-photon emission has approached the transform-limited regime. To this end, we adopt two complementary figures of merit, inspired by methods in other solid-state systems [55]. The first is the linewidth ratio $R = W_{\text{exp}}/W_{\text{dec}}$, which compares the measured emission linewidth W_{exp} with the Fourier-limited linewidth inferred from the decay time ($W_{\text{dec}} = h/2\pi\tau_{\text{dec}}$) [58]. This ratio provides a measure of how closely an emitter approaches the transform-limited regime, with $R = 1$ representing the ideal, noise-free case. The total broadening $\Delta W = W_{\text{exp}} - W_{\text{dec}}$ is our second figure of merit, which captures the absolute spectral contribution from dephasing and noise. Although W_{dec} is not strictly identical to the radiative-limited linewidth W_{rad} —since relaxation processes can also contribute to

τ_{dec} —it provides a conservative proxy ($\tau_{\text{dec}} > \tau_{\text{rad}} \Rightarrow W_{\text{dec}} < W_{\text{rad}}$). Hence, W_{dec} provides a lower limit for W_{rad} , ensuring that the resulting values of both R and ΔW are conservative estimates. We express the total measured linewidth as

$$W_{\text{exp}} = W_{\text{dec}} + W_{\text{PD}} + W_{\text{noise}}, \quad (1)$$

where W_{PD} accounts for broadening due to phonon dephasing, and W_{noise} captures extrinsic fluctuations, primarily charge noise. While phonon coupling is an intrinsic limitation [59,60] and its mitigation falls outside the scope of this work, theoretical estimates suggest that W_{noise} dominates the total broadening by up to 4 orders of magnitude, representing a key bottleneck for achieving indistinguishable single-photon emission in TMD quantum emitters [42].

To systematically evaluate the impact of our noise mitigation strategies, we extract the experimental linewidths W_{exp} and Fourier-limited linewidths W_{dec} as a function of applied biases from device B. Device A, which serves as an unmitigated reference, is included only at zero bias. As summarized in Fig. 5(a), h -BN encapsulation alone reduces W_{exp} from 474.6 μeV (device A) to 141.5 μeV (device B, $V_{\text{bias}} = 0$ V). With increasing bias, the linewidth narrows further, reaching below 100 μeV at $V_{\text{bias}} = \pm 10$ V, limited by the spectrometer's resolution limit. Although a slightly narrower linewidth is observed for $V_{\text{bias}} = 7$ V and $V_{\text{bias}} = 10$ V, the value of W_{exp} is less reliable since it is derived from data with a high signal-to-noise ratio near the resolution threshold.

Corresponding W_{dec} values are calculated values obtained from the TRPL decay times at each bias voltage [Fig. 5(b)]. The results reveal a clear bias-dependent trend, with lifetimes decreasing under negative bias and increasing under positive bias, exhibiting a total variation of approximately $\pm 40\%$ relative to the unbiased case. This variation translates into a corresponding shift in W_{dec} , with shorter lifetimes yielding broader Fourier-limited linewidths. While W_{dec} remains well below W_{exp} under all conditions, the observed changes likely reflect a modulation in the emitter's recombination dynamics due to perturbations to the local electrostatic environment induced by the applied bias. Because of significant PL quenching at higher bias, measurements beyond $V_{\text{bias}} = +5$ V are excluded.

With both W_{exp} and W_{dec} extracted across different bias conditions [Figs. 5(a) and 5(b)], we now combine these quantities to calculate the two key figures of merit that quantify the proximity to the transform-limited emission and the extent of charge-induced broadening. Figure 5(c) presents the linewidth ratio $R = W_{\text{exp}}/W_{\text{dec}}$, while Fig. 5(d) shows the absolute broadening $\Delta W = W_{\text{exp}} - W_{\text{dec}}$, each compared against the unencapsulated device A as a reference. We find that h -BN encapsulation alone reduces R significantly from ~ 4314 in device A to ~ 2100 in the

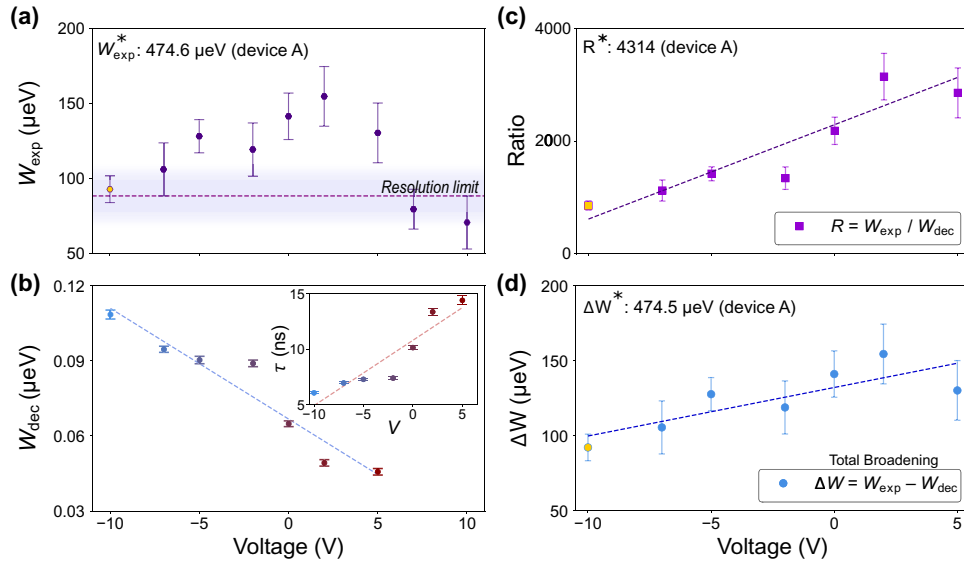


FIG. 5. Voltage-dependent analysis of the measured (W_{exp}) and Fourier-limited (W_{dec}) linewidths and the correlated broadening mechanisms. (a) Measured linewidth W_{exp} as a function of applied bias. At both extrema ($V_{\text{bias}} = \pm 10 \text{ V}$), W_{exp} reaches the resolution limit ($\sim 100 \mu\text{eV}$), while near $V_{\text{bias}} = 0 \text{ V}$, it remains close to its intrinsic value. Notably, the data point at $V_{\text{bias}} = -10 \text{ V}$ is highlighted, as it corresponds to the highest emission intensity. In contrast, at $V_{\text{bias}} = +10 \text{ V}$, the intensity is negligible, effectively rendering the emitter nonfunctional. Additionally, we include the value of the exemplary emitter in device A at zero bias. This value is approximately 3 times larger than in the encapsulated case at 0 V bias and more than 5 times larger than the values observed at $\pm 10 \text{ V}$. (b) Extracted Fourier-limited linewidths W_{dec} from time-resolved photoluminescence measurements as a function of applied bias. As the bias transitions from negative to positive values, W_{dec} decreases, resulting from an increase in the emitter's measured decay time. This inverse relationship is further illustrated in the inset, where the lifetime is plotted against bias, exhibiting the expected opposite trend, consistent with $W_{\text{dec}} \simeq 1/\tau$. Additionally, the data points are color-coded to correspond to their respective bias values, for ease of interpretation. (c) Ratio $R = W_{\text{exp}}/W_{\text{dec}}$ as a function of voltage. The decreasing trend when moving toward negative voltage values arises from the simultaneous decrease of W_{exp} and increase of W_{dec} , indicating that the two values approach each other in the voltage range where the emitter is most useful (i.e., higher emission intensity). R^* represents the ratio for device A, twice as large as for the unbiased case in device B and 5 times as large as for the optimized ($V_{\text{bias}} = -10 \text{ V}$) case. (d) Total broadening of the emitter, defined as $\Delta W = W_{\text{exp}} - W_{\text{dec}}$, as a function of voltage. Once more, a decreasing trend is observed toward negative voltages, reaching below $100 \mu\text{eV}$ at $V_{\text{bias}} = -10 \text{ V}$. The value for device A (ΔW^*) is more than 5 times larger than the lowest value achieved for device B at $V_{\text{bias}} = -10 \text{ V}$.

unbiased device B. Introducing electrical bias further suppresses R , reaching a minimum value of ~ 860 at $V_{\text{bias}} = -10 \text{ V}$. This nearly fivefold reduction brings the emitter substantially closer to the transform-limited regime. It is worth noting, however, that R depends strongly on the radiative lifetime, which can vary widely among TMD emitters, from less than 1 ns to tens of nanoseconds. Consequently, values of R calculated on the basis of the results presented in other studies span a broad range, from below 100 to several thousand (see Table 1 in Supplemental Material [51]). In our case, despite W_{exp} approaching the resolution limit, the minimum R remains ~ 860 —higher than the best-reported value of ~ 270 for WSe₂ emitters with lifetimes of around 1.5 ns [43]. This apparent discrepancy can be misleading when one is evaluating proximity to the transform-limited regime, and is caused solely by the difference in radiative lifetimes, well inside the expected range.

The absolute spectral broadening ΔW , shown in Fig. 5(d), follows a similar trend. Encapsulation alone reduces ΔW from $474.5 \mu\text{eV}$ (device A) to $\sim 140 \mu\text{eV}$ (device B), while electrical bias further narrows it to a minimum of $92.8 \mu\text{eV}$ at $V_{\text{bias}} = -10 \text{ V}$. This more than fivefold reduction confirms that combining h -BN encapsulation with electrical biasing is highly effective in suppressing charge noise and subsequently narrowing spectral linewidths in WSe₂ quantum emitters. Notably, the value of ΔW at $V_{\text{bias}} = -10 \text{ V}$ surpasses the best previously reported for WSe₂ and related materials, indicating that such levels of noise suppression can be reached without relying on complex fabrication strategies or cavity-enhanced emission [44]. Still, as with R , care must be taken in interpreting ΔW , since it is fundamentally limited by the spectral resolution used to measure W_{exp} . Many studies lack the high-resolution techniques necessary to resolve intrinsic linewidths, and instead report lower-bound estimates that

sacrifice resolution in favor of other experimental priorities. In contrast, our measurements already reach the resolution limit of a standard optical spectrometer, indicating that the true intrinsic linewidth may be even narrower. This underscores the need for advanced spectroscopic approaches, such as interferometric or cavity-enhanced techniques, to accurately resolve the transform-limited emission regime in future studies.

Beyond demonstrating the effectiveness of *h*-BN encapsulation and electrical biasing in suppressing charge noise, our analysis of both R and ΔW provides a practical and quantitative framework for benchmarking the performance of quantum emitters in TMD materials. Together, these complementary figures of merit enable a more nuanced and reliable assessment of emitter quality and proximity to the transform-limited regime.

III. DISCUSSION

Our findings demonstrate that the combination of *h*-BN encapsulation and electrostatic biasing offers an effective strategy for mitigating charge noise in WSe₂ quantum emitters, advancing their performance toward the transform limit of single-photon emission. Encapsulation alone leads to substantial improvements in single-photon emission, evidenced by significantly reduced linewidths and suppressed spectral wandering. These enhancements are attributed to the electrostatic screening provided by the *h*-BN layers, which isolate the emitter from a noisy charge environment (e.g., substrate). Supporting this interpretation, TRPL measurements reveal a transition from biexponential decay, indicative of nonradiative decay channels, in unencapsulated emitters, to monoexponential decay in encapsulated devices. Furthermore, second-order correlation measurements confirm high single-photon purity of 99%, with no observable bunching even at longer timescales ($\pm 25 \mu\text{s}$), suggesting the absence of blinking in the device.

Electrostatic biasing provides an additional enhancement in emitter performance while allowing for tunability and control. However, its benefits are realized only when it is used in conjunction with encapsulation. While unencapsulated devices suffer from increased instability and possible quenching under bias, encapsulated emitters exhibit robust and reversible linear Stark tuning and further linewidth narrowing. Remarkably, the linewidths under bias reach the resolution limit of our spectrometer, without compromising long-term spectral stability. Simultaneously, we observe a radiative lifetime modulation of up to $\pm 40\%$, suggesting that biasing can also influence the recombination dynamics in the system.

To quantify the impact of our noise mitigation strategies, we introduced two figures of merit: the linewidth ratio $R = W_{\text{exp}}/W_{\text{dec}}$ and the total broadening $\Delta W = W_{\text{exp}} - W_{\text{dec}}$.

These metrics provide a consistent and quantitative measure of how close an emitter approaches transform-limited behavior. In device B, we observe a fivefold reduction in both R (from 4314 to 860) and ΔW (from 474.5 to 92.8 μeV) relative to the unencapsulated and unbiased reference (device A). In the charge-noise-dominated regime, we observe that while W_{exp} decreases significantly under applied bias, the extracted W_{dec} remains nearly unchanged. This divergence implies that W_{noise} , which dominates W_{exp} at zero bias, is effectively suppressed. Since W_{PD} (phonon dephasing) is temperature limited and bias independent, the reduction in W_{exp} can be attributed primarily to charge-noise mitigation. While the measured W_{exp} reaches our setup's resolution limit, it does not reflect the true intrinsic linewidth of the emitter. This highlights the need for higher-resolution spectroscopic techniques to resolve this regime. Moreover, the relatively high value of R , driven by the long radiative lifetime ($\sim 6 \text{ ns}$), likely underestimates the actual proximity to the transform limit.

To that end, there are several viable pathways to reduce R even closer to the transform limit. A promising approach lies in implementing advanced optical excitation schemes, e.g., phonon-assisted, resonant, and swing-up of quantum emitter population (SUPER), in contrast to a standard above-band excitation [9,45,61–63]. For instance, phonon-assisted excitation schemes have been shown to reduce radiative lifetimes to $\sim 1 \text{ ns}$ for the case of WSe₂ quantum emitters [45]. If implemented in device B under a proper bias, such an emitter with reduced lifetime could yield an R value of ~ 150 , bringing it significantly closer to the transform limit. Furthermore, integrating device B into an optical cavity with a modest Purcell factor of ~ 10 , combined with an optimized excitation scheme, could reduce the lifetime to $\sim 0.1 \text{ ns}$ [31,41,53]. This would enable an improved R value of ~ 15 , just 1 order of magnitude away from the ideal transform-limit performance.

IV. CONCLUSION

In conclusion, we demonstrated how the combination of *h*-BN encapsulation and electrostatic biasing can improve the emission properties of WSe₂ quantum emitters, while also providing a consistent framework for benchmarking their performance. Specifically, we showed that *h*-BN encapsulation alone reduces both the emission linewidth and spectral wandering, bringing them down to approximately 150 μeV and 40 μeV , respectively. In addition, time-resolved measurements confirm a stable electrostatic environment through a monoexponential decay, and second-order correlation measurements reveal a high single-photon purity ($\sim 99\%$) with no observable blinking. When electrostatic biasing is applied in conjunction with encapsulation, the emitter performance is further enhanced. The linewidth reaches the resolution

limit ($\sim 100 \mu\text{eV}$), without compromising long-term stability, and the emission energy becomes tunable over a range exceeding $280 \mu\text{eV}$. The progress toward transform-limited emission is assessed through two figures of merit, the linewidth ratio R and the total broadening ΔW , both of which show more than a fivefold improvement in the optimized devices. These results provide a clear pathway toward the development of low-noise and tunable WSe_2 quantum emitters, potentially realizing electrically controllable sources of indistinguishable single photons for future photonic quantum technologies.

V. MATERIALS AND METHODS

A. Sample preparation

1. Nanopillar fabrication

The wafer consists of 110 nm of SiO_2 grown by thermal oxidation on a Si wafer. Alignment marks were fabricated by spin-coating and patterning UV resist (AZ 5214-E, MicroChemicals), followed by physical vapor deposition of Ti(5 nm)/Au(50 nm) and a liftoff process. For the fabrication of the nanopillars, a small chip is cleaved from the wafer and spin-coated with a high-resolution negative electron-beam resist (hydrogen silsesquioxane, XR-1541-006, Dow Corning) at 3000 revolutions/min for 1 min, followed by two soft baking steps at 120 and 220 °C, both for 2 min. The resist was patterned (JBX-9500FS, JEOL, 100 kV, 6 nA) with a dose of $11\,000 \mu\text{C}/\text{cm}^2$ and developed in a 1:3 solution of AZ 400K and H_2O to obtain 150-nm-tall (device A) or 250-nm-tall (device B) nanopillars in the shape of a three-pointed star.

2. Exfoliation and transfer

WSe_2 flakes were first exfoliated from bulk crystals (HQ Graphene) via the Scotch-tape method [64]. The flakes were then deposited on a polydimethylsiloxane (PDMS) stamp, which was prepared on a glass slide. The monolayers were identified by photoluminescence measurements with the use of an optical microscope (Nikon $20\times$, numerical aperture 0.45) and a 450 nm light-emitting diode excitation source. The transfer of the flakes to the nanostructures was performed with the help of a transfer stage that could heat the chip to 70 °C. At this temperature, the van der Waals interactions between the flake and the substrate overcome the adhesion to PDMS, and the flake is released from the polymer.

3. Defect fabrication

Defects were introduced on the monolayer lattice by bombarding the strained areas of the material with an electron beam (JBX-9500FS, JEOL, 100 kV, $1000 \mu\text{C}/\text{cm}^2$).

B. Optical characterization

1. Photoluminescence measurements

The PL measurements were obtained with a custom-built low-temperature μPL setup. The sample is mounted on a closed-cycle cryostat (attoDRY800, Attocube) operating at a base temperature of 4 K. The cryostat is equipped with piezoelectric nanopositioners and a low-temperature microscope objective ($60\times$, numerical aperture 0.82) located inside the cryostat. For the μPL spectroscopy, a CW and pulsed (20 and 80 MHz) laser diode at 650 nm (LDH-D-C-650, PicoQuant) was used for the optical excitation of the emitters. The PL spectra were acquired with a fiber-coupled signal directed to a spectrometer (iHR 550, Horiba) equipped with 600 or 1200 lines per millimeter gratings and a charged-coupled device camera (Syncerity, Horiba).

2. Time-correlated measurements

Time-correlated single-photon-counting mode was used to perform time-resolved PL characterization and single-photon statistics measurements. For second-order correlation measurements, we used a fiber-optic-based Hanbury-Brown and Twiss interferometer. The photon counting was conducted with superconducting nanowire single-photon detectors (ID218, ID Quantique) connected to a time-correlated single-photon counting module (Time Tagger Ultra, Swabian Instruments).

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A.P. and P.M. fabricated all the samples. A.P., P.W., P.M., and B.M. performed optical measurements on the fabricated samples. A.P. and P.W. contributed to data analysis and processing. B.M. conceived the idea, and N.G. and B.M. coordinated the project. A.P., P.M., and B.M. wrote the manuscript with input from all co-authors.

The authors declare they have no competing financial interest.

DATA AVAILABILITY

The data that support the findings of this article are openly available [76].

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